

Performance monitoring techniques for semiconductor pixel detectors in long-term operations*

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Semiconductor pixel detectors are widely used in various applications, many of which require sustained stability of the detector performance over extended periods of operations. However, the presence of irreversible and temporary degradations can impact the performance of the detector over extended periods of use. Thus, maintaining continual monitoring of the detector performance that is susceptible to degradation effects become necessary. This paper presents a cost-effective examination procedure for real-time monitoring and regular inspections of pixel detectors during prolonged operations. The real-time monitoring method monitors the charge drifting process without introducing additional background by utilizing the cosmic muons to identify temporary effects caused by shifts in operating conditions, such as ambient temperature fluctuations. On the other hand, the offline inspection regularly evaluates the per-pixel spectral characteristics including baseline and gain using simple radioactive sources to evaluate the extent of irreversible degradation. The monitoring procedure is validated on a Timepix3 detector equipped with a CdTe sensor which proves its effectiveness.

Keywords: Semiconductor pixel detectors, Real-time performance monitoring, Regular performance inspection, Performance monitoring with muons

I. INTRODUCTION

Semiconductor pixel detectors are widely utilized in diverse fields such as medical imaging [1, 2], electron microscopy [3, 4], radiotherapy [5, 6], and scientific research, including particle accelerator experiments [7], low-background studies like the search for $0\nu\beta\beta$ decay [8] as well as high flux studies like diagnostic systems in fusion devices [9–11]. In some applications like the low-background experiments, continuous data acquisition is required, which necessitates prolonged stability of the detector [8]. Applications for medical and scientific purposes like medical imaging and electron microscopy may not require constant operation, but still demand consistent detector performance over extended periods of usage [12–15]. However, prolonged usage exposes detectors to temporary and even irreversible performance degradation. The temporary performance degradation can be caused by variations in the operating conditions such as changes in the environment temperature. This type of degradation can affect the charge collection process in detectors with sensor materials such as silicon [16], CdTe [42] as well as GaAs [17] and result in fluctuations of the detector response. Additionally, intrinsic properties of the sensor material, such as polarization effect in CdTe detectors [33–39], can also cause distortions in the captured physical signals. Both of the aforementioned cases can potentially yield anomalous

data. On the other hand, irreversible performance degradation can result from aging effects, such as interface deterioration in CdZnTe detectors [32] and radiation-induced damage caused by either accumulated exposure or high flux irradiation. Such damage typically occurs when the integrated particle flux reaches $10^{13} - 10^{16}$ p/cm² for proton irradiation [18, 21, 22, 25, 28], photon irradiation [19, 20, 24, 26, 27, 30] and electron irradiation [27, 29]. It can lead to distorted and reduced charge collection efficiency (CCE) as well as increased leakage current in silicon [18, 21, 22, 30], CdTe [20], CdZnTe [20, 23–26], GaAs [27–29] and SiC [19, 30] detectors. The cumulative impact of these aging effects over time results in deteriorating detector performance and eventually leads to signal distortion and degradation in the measured data. In scenarios with high particle flux, such as the diagnostic systems in fusion devices [9–11], aging effects due to radiation damage can cause the detectors to cease operation, leading to a complete loss of data, or create unwanted background data [9]. Therefore, continuous monitoring of the detector performance and stability during long-term operations is essential. To identify the temporary performance degradation, it is necessary to monitor the key aspects of detector performance, namely the parameters associated with the charge collection process, in real-time. Once the temporary shifts in the detector response are detected, appropriate measures such as temperature stabilization can be taken to mitigate the changes effectively. On the other hand, the extent of irreversible degradation should be assessed via regular evaluations of the detector performance, encompassing factors like the leakage current and CCE that can affect the operating parameters such as baseline [31] and gain. Subsequently, energy calibration and gain correction may be essential to sustain the functionality of the detectors. In cases where the degrada-

* Supported by the National Natural Science Foundation of China (Grant No. 12305228)

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tion exceeds permissible levels, replacement of the detectors would be needed. These performance monitoring procedures are helpful in maintaining data integrity and avoiding the inaccuracies beforehand, particularly in applications like diagnostic systems in fusion devices where the measurements are costly and lengthy, and the replacement of detectors must be performed offline. There are existing methods to calibrate the aforementioned aspects of detector performance susceptible to degradation. Parameters related to the charge collection process can be determined utilizing energetic charged particles, such as pions generated by accelerators [43] and cosmic muons [4, 44]. However, these measurements are typically performed outside the regular operational periods. Such measurements can be more advantageous if they can be performed in real time since the charge collection process is primarily affected by the temporary degradation that may vary over time. Additionally, the effects induced by irreversible degradation, namely increased leakage current and reduced CCE, leads to elevated electronic noise levels, raised detector baseline and reduced detector gain. Thus, identifying these effects involve offline assessment of the detector baseline and gain. While both procedures are currently well-established, the gain assessment often entails the use of radiation apparatus such as X-ray devices. This poses challenges for regular inspections, especially in industrial and medical settings where numerous detectors are deployed. In order to overcome the limitations with the existing evaluation methods in identifying performance degradations over extended periods of operation, it is necessary to implement a cost-effective approach that integrates online monitoring with regular offline inspections. This approach is crucial for the timely detection of performance deterioration and early warning of potential detector failures or anomalous data.

This paper introduces a low-cost detector monitoring procedure to facilitate regular assessments of the detector performance. The procedure utilizes cosmic muons to monitor the charge collection process in real time, alongside periodic inspections using easily procurable low-activity calibration sources to assess the characteristics susceptible to irreversible degradation. This approach can be used to effectively monitor the detector performance that can be impacted by temporary and irreversible degradation during long-term operations. The proposed method is validated on MiniPIX TPX3, a Timepix3 detector manufactured by ADVACAM. The detector is equipped with a 1 mm-thick CdTe sensor which has an active area measuring $14.08 \times 14.08 \text{ mm}^2$ and a total of 256×256 pixels with a pixel size of $55 \text{ }\mu\text{m}$. A schematic of the sensor structure is given in Fig. 1(a).

II. PERFORMANCE MONITORING METHODS

The proposed performance monitoring procedure comprises two types of measurements: real-time monitoring and offline inspection. The real-time monitoring focuses on monitoring changes in the charge collection process to identify the temporary degradation. This approach is developed based on

the previously reported charge carrier drift time calibration method utilizing cosmic muons [4, 44]. This monitoring procedure can be conducted concurrently with normal operation without the need for additional radioactive sources, thereby avoiding the introduction of extra background noise. On the other hand, the offline inspection is designed to evaluate the detector characteristics, such as baseline and gain, that are susceptible to irreversible degradation. Unlike conventional methods that are reliant on radiation apparatus, this method only requires simple, low-activity radioactive sources and can be implemented cost-effectively. It is well-suited for applications in the medical and industrial sectors that involve a large number of detectors. Detailed descriptions of the performance monitoring procedure are provided in the following sections.

A. Real-time monitoring of charge collection process

The real-time monitoring process is specifically designed to monitor the distribution of the internal electric field and assess the behaviour of charge carriers as they drift, providing insights into the charge collection efficiency within the sensor. As discussed in the previous section, this procedure relies solely on cosmic muons, which tend to follow straight trajectories within the sensor. This approach has been documented in previous studies [4, 43, 44]. Here, we present a comprehensive outline of the data selection and parameter extraction procedures.

Unlike previously proposed calibration method that requires dedicated cosmic muon measurements, our method utilizes the data gathered during normal operation to identify cosmic muon tracks for analysis. This data collection method allows for continuous monitoring of the detector response to detect time-varying changes by examining the data from any designated time frame. This endows the proposed method with real-time monitoring capabilities and enhanced flexibility. On the other hand, cosmic muons are also well-suited as a persistently existing calibration source for the continuous performance monitoring during long-term operations without introducing additional background, particularly in scenarios requiring a significant number of detectors. Following the data selection stage, the muon tracks are fitted to establish the relationship between the drift time of the charge carriers collected at the pixel electrode (electrons for detectors with pixel anodes or holes for detectors with pixel cathodes, referred to as “collected charge carrier” hereafter) and the depth of interaction. This correlation is instrumental in order to derive the electric field distribution. By leveraging the linear trajectories of energetic charged particles that traverse the full sensor thickness, these tracks can be reconstructed geometrically. This enables the establishment of a connection between the measured charge carrier drift time and the reconstructed interaction depth. The drift velocity of charge carriers at a specific depth z is given by

$$v(z) = -\frac{dz}{dt} = \mu E_{\text{int}}(z), \quad (1)$$

where μ is the mobility of the charge carrier and $E_{\text{int}}(z)$ is the internal electric field at the given depth. By integrating Eq. (1) the correspondence between interaction depth z_0 and drift time t_0 can be derived,

$$t_0 = \int_0^{z_0} \frac{dz}{\mu E_{\text{int}}(z)}, \quad (2)$$

which can be fitted using the reconstructed linear tracks of charged particles and thus the parameters of the internal electric field can be obtained. To identify these linear tracks from the data collected, an initial 2-dimensional linear fit is applied to the tracks along the pixel plane. Tracks with significant fit errors, such as the ones generated by non-muon particles and the ones with branches diverging from the primary particle tracks that are often generated by the secondary particles like δ -electrons (δ -rays), are excluded from further analysis. Subsequently, a 3-dimensional linear fit is conducted on the remaining tracks to eliminate any outlying pixel signals from the primary tracks. The tracks are then assessed for intersections with the pixel plane edges to filter out the tracks that do not traverse the entire sensor thickness. Furthermore, a small percentage of the pixels in the vicinity of the pixel plane are disregarded from the tracks due to substantial errors in drift time measurement in that area. A demonstration of the aforementioned track selection process using the data collected from the Timepix3 detector with a 1 mm CdTe sensor and applied bias voltage of -400 V is illustrated in Fig. 1.

Following the identification of linear tracks within the data, the interaction depth for each pixel along the tracks is reconstructed based on the sensor geometry. The reconstruction method proposed by Bergmann et al [43] is employed for this purpose. Initially, the entry point $\mathbf{P}_{\text{entry}} = (x_{\text{entry}}, y_{\text{entry}})$ at $z = 0$ and the exit point $\mathbf{P}_{\text{exit}} = (x_{\text{exit}}, y_{\text{exit}})$ at $z = d$ are determined for each track. Subsequently, the interaction depth of each pixel \mathbf{P} in the track can be computed with

$$z_{\text{geo}}(\mathbf{P}) = \frac{d}{L_{\text{proj}}} \cdot r(\mathbf{P}), \quad (3)$$

where d is the thickness of the sensor, $L_{\text{proj}} = |\mathbf{P}_{\text{exit}} - \mathbf{P}_{\text{entry}}|$ is the projected length of the track and $r(\mathbf{P}) = |\mathbf{P} - \mathbf{P}_{\text{entry}}|$ is the projected distance from the pixel \mathbf{P} to the entry point. Finally, the correlation between the interaction depth and drift time is derived from the reconstructed tracks and then fitted with Eq. (2) to obtain the electric field parameters.

In fully depleted detectors with sensor materials such as silicon and CdTe, the internal electric field typically exhibits a linear decay from the pixel electrode to the non-collecting electrode. In the case of fully depleted silicon sensors, the electric field can be characterized by [45]

$$E(z) = \left(\frac{U_B}{d} + \frac{U_D}{d^2} \left(\frac{d}{2} - z \right) \right), \quad (4)$$

with U_B being the applied bias voltage and U_D being the depletion voltage of the sensor. On the other hand, the electric field in CdTe sensor can be fitted with [43]

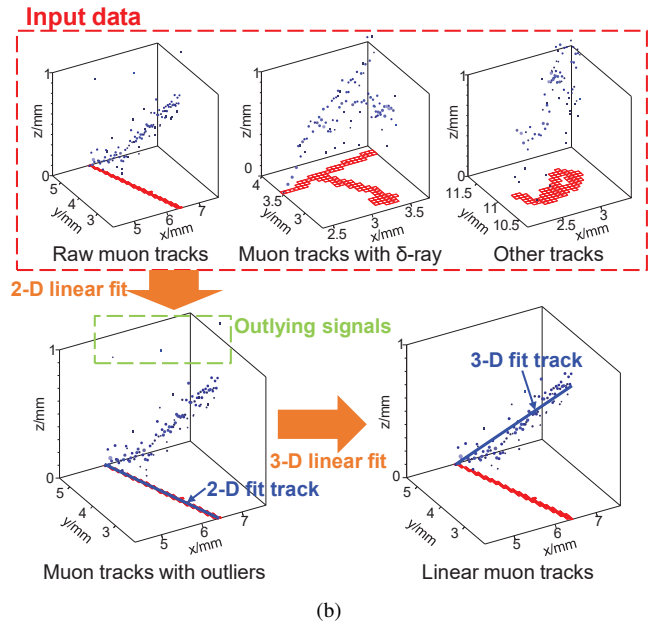
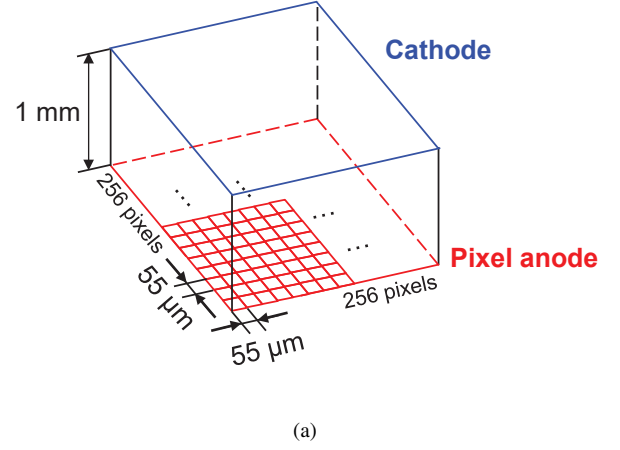


Fig. 1. (Color online) A demonstration of the muon track selection. (a) A diagram of the internal structure of the detector used for the demonstration. (b) Schematic of the muon track selection process. The pixel signals with 3-dimensional position information are marked in blue dots with the corresponding triggered pixels marked in red frames in the pixel plane. The linear muon tracks are picked out via 2-dimensional linear fit (marked with blue line), followed by a 3-dimensional linear fit to exclude the outlying pixel signals.

$$E(z) = -\frac{U_B}{d} \left(1 + \left(f_1 + \frac{f_2}{U_B} \right) \frac{z}{d} \right), \quad (5)$$

where f_1 and f_2 are the fitting parameters of the model. In this study, we employ the CdTe sensor as a representative example to illustrate the procedure of fitting and extracting the electric field parameters. Combining Eq. (2) and Eq. (5) yields

$$t_0(z_0) = -\frac{d^2}{\mu_e U_B (f_1 + f_2/U_B)} \cdot \ln \left(\frac{(f_1 + f_2/U_B)z_0}{d} + 1 \right), \quad (6)$$

which can be used to perform the fit. In the context of the CdTe sensor where electrons are the collected charge carriers, the mobility μ is substituted with the electron mobility μ_e in Eq. (6). However, for the detectors that are unable to register signals from the non-collecting electrode, determining the absolute drift time for each pixel becomes challenging. Instead, the drift time is derived by subtracting the recorded time-of-arrival (ToA) of the entry point from the ToA of each pixel. This approach may introduce a systematic error in the calculated drift times as the ToA measurement is significantly influenced by the non-collecting charge carriers (holes in the case of CdTe sensors) near the pixel electrode. To address this, a correction term t_{err} is introduced to Eq. (6) to factor in the systematic error of ToA. The adjusted fit function is then derived by rearranging Eq. (6),

$$z_0(t_0) = \frac{d}{f_1 + f_2/U_B} \left(\exp \left(-\frac{\mu_e U_B}{d^2} \cdot \left(f_1 + \frac{f_2}{U_B} \right) \cdot (t_0 - t_{\text{err}}) \right) - 1 \right). \quad (7)$$

While Eq. (7) offers a satisfactory representation for scenarios involving a linear electric field, it tends to diverge from the measured data in the vicinity of the pixel plane, as detailed in section. III. To address this discrepancy, an exponential correction term and a normalization coefficient are introduced to Eq. (5) to account for the deviations observed in the measured electric field

$$E_{\text{corr}}(z) = -C_{\text{norm}} \cdot \frac{U_B}{d} \cdot \left(1 + \left(f_1 + \frac{f_2}{U_B} \right) \frac{z}{d} + A \exp \left(-\frac{z}{L} \right) \right), \quad (8)$$

with C_{norm} being the normalization coefficient, A and L being the amplitude and decay length of the exponential term. The fit function representing the relationship between carrier drift time and interaction depth, as denoted by Eq. (6), can be appropriately adjusted in accordance with the introduced modifications,

$$t_0(z_0) = \int_0^{z_0} \frac{dz}{\mu_e E_{\text{corr}}(z)}, \quad (9)$$

and the coefficient C_{norm} can be obtained according to the bias voltage of the detector,

$$C_{\text{norm}} = -\frac{U_B}{\int_0^{z_0} E_{\text{corr}}(z) dz}. \quad (10)$$

B. Offline inspection of per-pixel spectral characteristics

The offline inspection serves the purpose of effectively capturing shifts in the per-pixel spectral characteristics including detector baseline and gain that can be influenced by the irreversible degradation. This process involves two distinct measurements, one to determine the baseline, which requires no additional radioactive sources, and another to assess the detector gain, utilizing easily procurable low-activity sources.

The initial phase of offline inspection involves a baseline scan, which is a well-established detector calibration procedure [46]. This process entails adjusting the threshold level of each pixel in close proximity to the baseline of the detector and recording the trigger count at each threshold value to outline the baseline distribution for each pixel. Subsequently, the average value of the baseline distribution indicates the baseline level of the corresponding pixel, and the standard deviation reflects the electronic noise present.

The following aspect of the offline inspection focuses on evaluating the detector gain to evaluate both the average gain of the detector and the gain consistency across various areas on the pixel plane. In addition to potential decrease in the overall detector gain, local reductions in the detector gain may also arise from aging effects. This local reduction can lead to significant gain discrepancies among different areas of the pixel plane. This spatial disparity can contribute to the degradation in the energy resolution of the detector, which further underscores the importance of regular assessments of spatial uniformity. Conventional gain evaluation method typically involves using radiation apparatus such as X-ray devices to generate low-energy photons (typically below 30 keV). These photons produce signals confined to a single detector pixel, enabling per-pixel of gain calibration [47]. In contrast, our method only utilizes simple radioactive sources like low-activity (~tens of μCi) ^{241}Am positioned adjacent to the non-collecting electrode for data collection. As the charge signal from the radioactive sources can spread across multiple pixels, the data analysis involves segmenting the detector into distinct regions, each containing one or a few pixels, and the size of each region determined by the average size of the full-energy events. To ensure accurate gain estimation for each region, data acquisition is conducted over a specific timeframe to gather sufficient data points per region. Subsequently, the spectrum collected from each region i is fitted with a Gaussian function to determine the center position μ_i of the full-energy peak. Ultimately, the average peak position $\bar{\mu}$ across all regions is computed, and the relative gain of each region is calculated with

$$G_i = \frac{\mu_i}{\bar{\mu}}. \quad (11)$$

III. RESULTS AND DISCUSSION

The proposed performance monitoring methodology is tested on a MiniPIX TPX3 detector equipped with a 1 mm thick CdTe sensor. The parameters associated with the charge

collection process, detector baseline, and detector gain are determined through real-time monitoring and offline inspection processes, respectively, utilizing only a single additional ^{241}Am source. Variations in the parameters associated with the charge collection process are showcased through data acquired from two 20-hour measurements employing the real-time monitoring techniques. The baseline level and electronic noise characteristics of each pixel are extracted from the baseline scan, while the assessment of overall detector gain and gain uniformity is based on the measurements performed with the ^{241}Am source.

322

323 A. Real-time monitoring of charge collection process

324 The real-time monitoring process involves utilizing data
325 from two sequential measurements, both performed at a de-
326 tector bias voltage of -400 V. Initially, the Timepix3 de-
327 tector is exposed to cosmic muons for 20 hours to gather data
328 (referred to as “measurement 1”). Since the detector has
329 been operating for several consecutive days before this mea-
330 surement, with the average temperature of the sensor reach-
331 ing around 35 °C, a 30-minute cool-down period is initiated
332 by switching off the detector after measurement 1. Subse-
333 quently, another 20-hour data collection session (referred to
334 as “measurement 2”) is conducted, with the sensor operat-
335 ing at approximately 25 °C. Despite the absence of external
336 temperature regulation during the measurements, the metal
337 casing surrounding the detector, combined with passive cool-
338 ing measures, was sufficient to mitigate abrupt temperature
339 changes in the sensor. Muon tracks are selected from the
340 datasets, and the correlations between charge carrier drift time
341 and interaction depth are fitted with Eq. (9) for each set of
342 data. As illustrated in Fig. 2, the fitting results exhibit discrep-
343 ancies in charge carrier drift time between the two measure-
344 ments. To further investigate the underlying reasons for these
345 disparities, the internal electric field distribution and electron
346 mobility are derived using Eqs. (8) and (10). Fig. 3 show-
347 cases the derived electric field distributions for measurements
348 1 and 2, with the fitted values of the parameters from Eqs. (8)
349 and (10) given in table 1. It is evident that the electric field
350 of the two measurements remain consistent despite the notable
351 fitting error in measurement 1, which suggests that the impact
352 of polarization in the sensor material is negligible. However,
353 there is a significant variance in electron mobilities between
354 the two measurements. Given that measurement 1 is con-
355 ducted at a higher average temperature (~35 °C) compared
356 to measurement 2 (~25 °C), the variation in electron mobil-
357 ity is most likely attributed to this temperature differential.
358 To address this, we extrapolated the electron mobility under
359 the condition of measurement 2 using the mobility derived
360 from measurement 1 and the theoretical electron mobility of
361 CdTe [48], which is also shown in table 1. The close agree-
362 ment between the measured and estimated electron mobilities
363 in measurement 1 confirms that the alternations in the charge
364 collection process is primarily caused by temperature fluctu-
365 ations. In practical applications, this monitoring procedure

366 can be employed to regularly monitor variations in the op-
367 erational conditions such as the ambient temperature. Upon
368 detecting such changes, appropriate measures such as stabi-
369 lizing the sensor temperature can be taken to maintain the data
370 integrity.

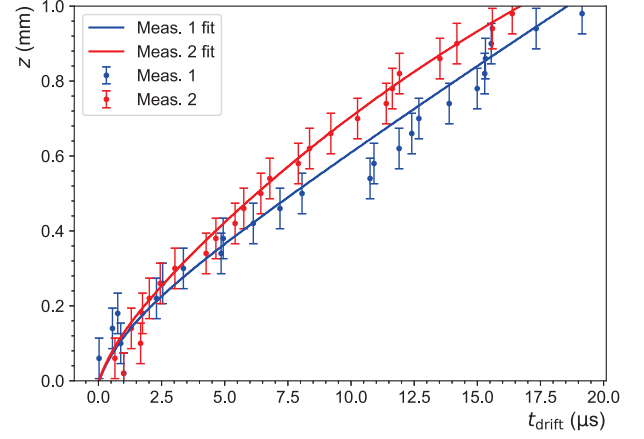


Fig. 2. (Color online) The correlation between carrier drift time and depth extracted from measurements 1 and 2, along with the fitting results.

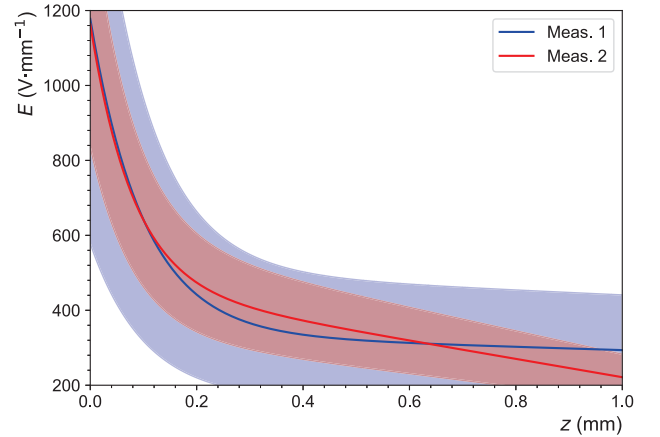


Fig. 3. (Color online) The electric field distribution calculated from the data of measurements 1 and 2.

372 B. Offline inspection of per-pixel spectral characteristics

373 The initial phase of the offline inspection involves con-
374 ducting a baseline scan as described in subsection II B with
375 the bias voltage set at -400 V. Following the acquisition of
376 baseline distributions from the scan data, the per-pixel base-
377 line level and electronic noise distribution are determined

TABLE 1. Fitted values of the operating parameters related to the charge collection process derived from measurements 1 and 2. Note that the estimated electron mobility of measurement 1 is calculated according to the result of measurement 2 and theoretical values [48].

Parameters	Result of measurement 1	Result of measurement 2
Temperature ($^{\circ}\text{C}$)	~ 35	~ 25
Electron mobility μ_e ($\text{m}^2 \cdot \text{V}^{-1} \cdot \text{s}^{-1}$)	15.09 ± 2.14	17.23 ± 1.29
Estimated electron mobility $\mu_{e,\text{est}}$ ($\text{m}^2 \cdot \text{V}^{-1} \cdot \text{s}^{-1}$)	16.69 ± 1.25	—
$f_1 + f_2/U_B$	-0.13 ± 0.25	-0.52 ± 0.06
A	2.17 ± 5.31	1.55 ± 2.71
L (μm)	86.9 ± 95.5	80.9 ± 62.8
C_{norm}	0.84 ± 0.42	1.16 ± 0.32

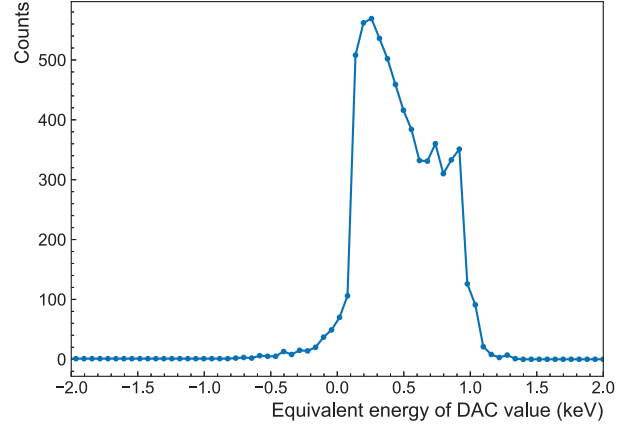


Fig. 4. (Color online) Demonstration of the baseline distribution derived from the baseline scan data from one pixel of the detector.

by the center and standard deviation of the baseline distribution of the corresponding pixel, as depicted in Fig. 4. It should be noted that the baseline level is determined by adjusting the output of the digital to analog converter (DAC) that regulates the threshold. Thus, the baseline levels are quantified in equivalent energy values derived from the DAC output values according to the energy calibration parameters. Fig. 5 displays the resultant per-pixel baseline and noise distribution which indicates an average baseline value of $E_b = (0.218 \pm 0.095)$ keV. Since the average detector baseline level was initially aligned to the equivalent energy of 0 keV during the energy calibration process of the factory test conducted under identical conditions, it is evident that the baseline of the detector has drifted from the calibrated values after 3 years of operation, in which the detector was irradiated with mostly gamma-ray photons with an accumulated flux of $\sim 3.19 \times 10^9 \text{ cm}^{-2}$. This rise in baseline level is most likely attributed to the increase in leakage current, which is most likely caused by aging effects. It signals a potential need for recalibration of the per-pixel energy response, which includes aligning the threshold DAC and the signal amplitude with the deposited energy. Additionally, the result provides a possible explanation to the deviation of the baseline distribution depicted in Fig. 4 from a standard Gaussian distribution. This deviation may stem from the response of the detector's preamplifier to signals of different polarities at increased baseline levels [46].

The subsequent segment of the offline inspection involves the assessment of detector gain. This procedure is carried out by exposing the detector to the 60 keV gamma rays of an ^{241}Am source placed at the incident window (cathode side) of the detector. Given the relatively low activity level (tens of μCi) of the ^{241}Am source, it is necessary for the measurement to last a prolonged period of 48 hours in order to accumulate an adequate amount of data to form the energy spectrum of each region. The bias voltage of the detector is set to -300 V. Based on the average event sizes in both x and y directions of the pixel plane, each region is configured to encompass 2×2 pixels. A depiction of the energy spectrum in one of the consequent 128×128 regions is shown in Fig. 6. The spectra are fitted using Gaussian functions,

and the fitted centers of the Gaussian peak indicate the gain in the corresponding regions. In order to evaluate the gain variation following 3 years of operation, a set of data collected under identical operating conditions is analysed using the same approach. After subtracting the per-pixel baseline level to accommodate the increase in baseline, the spectra of the 60 keV peak obtained in the current measurement (Dec. 2023) and 3 years prior (Sep. 2020) are compared in Fig. 7. The result indicates an evident decrease in detector gain that is likely caused by aging effects, which leads to the reduction in CCE. This shift in detector gain also necessitates the recalibration of the per-pixel energy response to ensure the correctness of the measured energy values. Furthermore, by normalizing the regional gain distribution with Eq. (11), the spatial gain uniformity is determined for both data and the results are showcased in Figs. 8(a) and 8(b). The comparison between the two figures reveals a decrease in local gain across several regions. Besides, a discernible pattern can be found in Fig. 8, which exhibits strong consistency between the two figures. This spatial distribution pattern in local gain has been reported in previous studies [47], which reported that it can result from calibration imperfections and sensor inhomogeneity. The spatial inhomogeneity of detector gain can be mitigated through per-pixel gain correction, utilizing the relative gain distribution derived from the gain assessment process.

IV. CONCLUSION

In this article, we introduce a new, cost-effective monitoring approach based on existing methodologies for semiconductor pixel detectors in long-term operations. This method combines the real-time monitoring to monitor the charge carrier drift process, which can be influenced by temporary effects, and the offline inspection to assess the per-pixel spectral characteristics including detector baseline and gain variations resulting from irreversible performance degradation. To validate the procedure, the real-time monitoring and offline in-

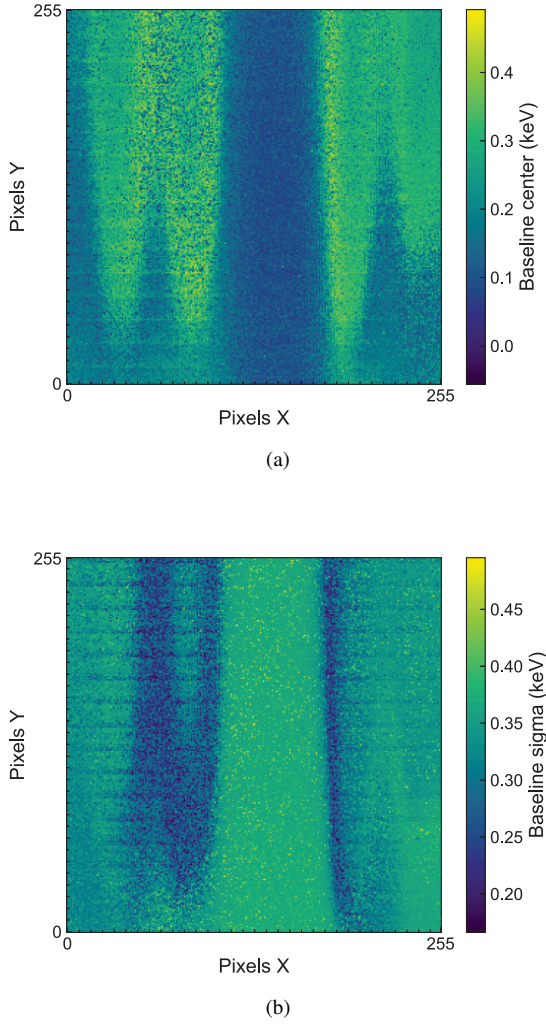


Fig. 5. (Color online) The baseline centers (a) and standard deviations (b) extracted from the baseline scan data via Gaussian fitting.

spections were conducted on a Timepix3 detector featuring a 1 mm-thick CdTe sensor. Results from real-time monitoring revealed shifts in the carrier drifting parameters due to temperature fluctuations. In practice, appropriate measures such as temperature stabilization need to be taken once such variations are identified. On the other hand, the offline inspection uncovered a rise in the detector baseline, a decrease in the detector gain and changes in spatial irregularities in per-pixel gain. These fluctuations in detector performance due to irreversible degradation indicates the necessity for recalibrations such as per-pixel energy calibration and corrections like spatial gain uniformity correction to be implemented. In conclusion, the aforementioned findings confirm the effectiveness of the proposed monitoring procedure in monitoring the perfor-

mance of pixel detectors.

While the monitoring procedure demonstrated effectiveness in detecting changes in CdTe pixel detectors, further validation on detectors with different sensor materials like sili-

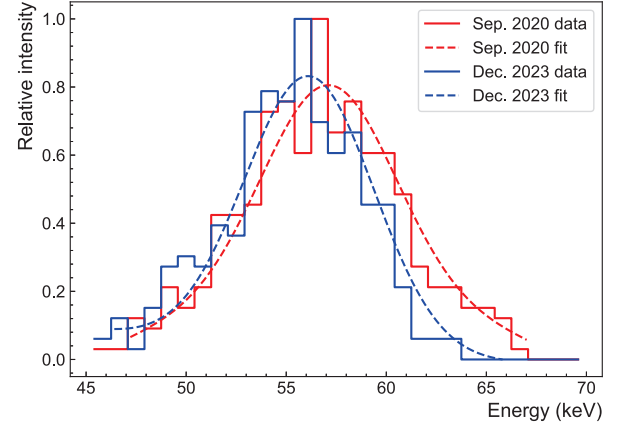


Fig. 6. (Color online) Depiction of the energy spectra of the 60 keV gamma rays from the ^{241}Am source in one of the 2×2 -pixel regions collected in Sep. 2020 and Dec. 2023 with the corresponding Gaussian fitting results.

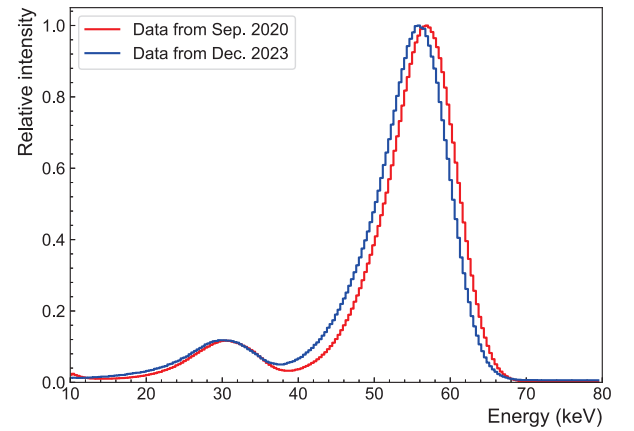


Fig. 7. (Color online) Comparison between the energy spectra of the 60 keV gamma rays from ^{241}Am source collected in Sep. 2020 and Dec. 2023.

con is warranted. Additionally, testing under actual long-term operational conditions, including aging tests and exposure to high-flux particle beams, is essential. After rigorous testing and refinement based on the test results, the monitoring procedure can be applied in fields requiring long-term operations. Such procedure offers a cost-efficient approach to regularly monitor detector performance, especially in industrial and medical applications with numerous detectors.

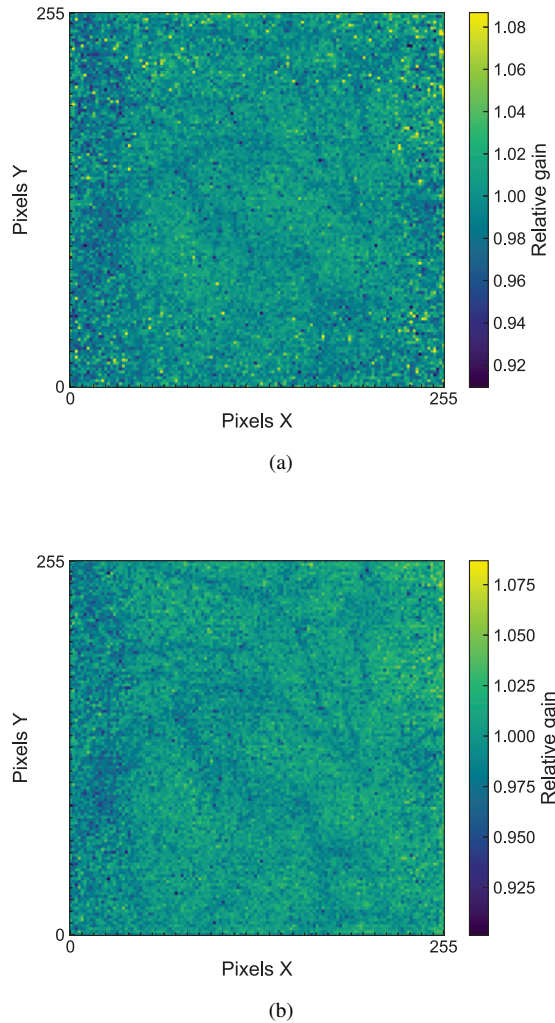


Fig. 8. (Color online) Comparison between the spatial gain uniformity derived from the measurement with the 60 keV gamma rays from ^{241}Am source collected in (a) Sep. 2020 and (b) Dec. 2023.

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